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Cyclotron Modeling Phase-Resolved Infrared Spectroscopy of Polars I: EF Eridani

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ABSTRACT

We present phase-resolved low resolution infrared spectra of the polar EF Eridani obtained over a period of 2 years with SPEX on the IRTF. The spectra, covering the wavelength range $0.8 \leq \lambda \leq 2.4 \mu\text{m}$, are dominated by cyclotron emission at all phases. We use a “Constant Lambda” prescription to attempt to model the changing cyclotron features seen in the spectra. A single cyclotron emission component with $B \simeq 12.6 \text{ MG}$, and a plasma temperature of $kT \simeq 5.0 \text{ keV}$, does a reasonable job in matching the features seen in the H - and K -bands, but fails to completely reproduce the morphology shortward of $1.6 \mu\text{m}$. We find that a two component model, where both components have similar properties, but whose contributions differ with viewing geometry, provides an excellent fit to the data. We discuss the implications of our models and compare them with previously published results. In addition, we show that a cyclotron model with similar properties to those used for modeling the infrared spectra, but with a field strength of $B = 115 \text{ MG}$, can explain the GALEX observations of EF Eri.

Subject headings: Cataclysmic Variables: general — Polars: EF Eri

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1. Introduction

Polars, or AM Herculis stars, constitute an important subclass of the cataclysmic variables (CVs) where the white dwarf primary is highly magnetic (see Wickramasinghe & Ferrario 2000 for a review). Like non-magnetic CVs, polars are interacting binary systems containing white dwarf primaries (WD) and low-mass main sequence secondary stars. The accretion pathway of non-magnetic CVs is well known; matter flows from the secondary star through the inner-Lagrangian point, free-falling until it settles into an accretion disk around the primary star. However, in polars the large magnetic field of the primary WD alters the system characteristics in the following three ways. First, the magnetosphere deflects material from its ballistic trajectory before an accretion disk can form. Secondly, polars are phase-locked. Dipole-dipole interactions between the primary and secondary star cause the rotation period of each star to relax to the orbital period of the system on a relatively short time-scale. Finally, polars have magnetic fields which usher accreting matter to a stationary accretion column. These occur at one/both of the magnetic poles of the WD in the ideal, dipolar case.

As the material is transported to the accretion region, the plasma is ionized mainly as a result of particle collisions, and from X-ray heating by the accretion region itself. For large mass accretion rates, a standing hydrodynamic shock is formed near the white dwarf photosphere, with shock heights usually several percent of its radius. Downstream from the shock, the electrons gyrating around the magnetic field emit cyclotron radiation. Lamb & Masters (1979) suggested this as the primary cause of the large optical linear and circular polarization ($\sim 10\%$), from which Tapia (1977a) had deduced a magnetic field strength of ~ 200 MG for AM Her (now known to have a primary field strength of 12 ± 0.5 MG; Kafka et al. 2006), a result which firmly established the high magnetic field strengths of these objects. Much of the cyclotron radiation emitted near the shock travels downward and is absorbed by the stellar photosphere, where it can be reprocessed. Low Accretion Rate Polars (LARPs) are defined as polars in which $\dot{m} \leq 1 \text{ g s}^{-1} \text{ cm}^{-2}$ over the accretion spot, corresponding to $\dot{M} \leq 1 \times 10^{-14} \text{ M}_{\odot} \text{ yr}^{-1}$ at L_1 . In such systems the timescale required to effectively cool the particle stream from its free-fall energy is less than a mean free path through the stellar atmosphere. This disrupts the formation of the hydrodynamic shock, and causes radiation to be emitted at temperatures lower than those predicted by strong shock models (c.f., Fabian et al. 1976), directly depositing the particle stream on to the stellar photosphere in the “bombardment scenario” (Kuijpers & Pringle, 1982; Thompson & Cawthorne, 1987).

EF Eri is an ultra-short period polar ($P_{\text{orb}} = 81$ minutes), that has remained an object of considerable interest since entering an extended low state in 1997 (Wheatley & Ramsay 1998). Recent SMARTS data indicate that it has stayed at $V = 18.2 \pm 0.1$ since that time

with only one exception: a brief flare of 2.5 mag on 2006 March 05 (Howell, S., private communication). EF Eri quickly returned to its low state two weeks later. Aside from this isolated event, EF Eri has continued in a nearly identical low optical state for at least the last 10 years.

Ferrario et al. (1996) detected cyclotron harmonics in an orbitally phase-averaged near-infrared spectrum of EF Eri in its high state, and found that a model with two different magnetic field strengths ($B_1 = 16.5$ MG, $B_2 = 21.0$ MG) best fit their data. Using Zeeman splitting of the Balmer lines, Wheatley & Ramsay (1998) derived a field strength of 13 MG. More recently Reinsch et al. (2003), and Beuermann et al. (2007) employed Zeeman tomography to map the field structure over the surface of the white dwarf. In the highest order multipole expansion considered ($l_{\max} = 5$) EF Eri was found to possess complex zones and/or bands of varying field strength containing regions of low field strength ($B \sim 10 - 15$ MG), as well as a well-defined ~ 100 MG pole.

Below we present new phase-resolved spectra of EF Eri in the infrared showing that large, variable cyclotron features are clearly responsible for the near-IR photometric variations observed by Harrison et al. 2004 (henceforth, H04). In the next section we describe our observations, in section 3 we fit these data with a changing cyclotron model, discuss our results in section 4, and draw our conclusions in section 5.

2. Observations

EF Eri was observed using SPEX on the Infrared Telescope Facility (IRTF) on the nights of 2004 August 17, and 2007 January 14. SPEX was used in low-resolution “prism” mode with a $0.3'' \times 15''$ slit. To remove background, we nodded EF Eri along the slit in an ABBA pattern. In its low-resolution mode SPEX produces $R \sim 250$ spectra, with short enough exposure times to obtain phase-resolved spectra of polars with $K \leq 16.0$. For the two epochs of observation, we used 240 second and 360 second exposure times, respectively, which were then median combined with 2-3 other spectra to allow for cosmic-ray removal and to increase the S/N ratio. The spectra were reduced using the SPEXTOOL package (Vacca et al. 2003). A telluric correction was applied using an A0V star of similar airmass to EF Eri. The stacked series of phase-resolved spectra are shown in Fig. 1 covering 0.8 to $2.4 \mu m$. The observed spectra are dominated by a series of broad features which can only be construed as cyclotron features. Despite the existence of a new spectroscopic ephemeris for EF Eri (Howell et al. 2006a) we have phased our spectra using the photometric ephemeris of Bailey et al. (1982) to enable direct comparison with previously published lightcurves.

During the 2004 August observations, a telescope issue resulted in only partial phase coverage. Thus, we returned in 2007 January to obtain full orbital coverage of EF Eri. There appears to have been little change in the phase-dependent morphology of the spectra in the intervening three years. Given the narrow slit width (0.3”) of SPEX, flux calibration of the spectra is uncertain. Thus, we have used the 2001 *K*-band light curve fluxes presented in H04 to flux calibrate the spectra in this bandpass at each phase. H04 also showed that the WD contributes up to 67% of the *J*-band flux near *J*-band minimum. We found that it was necessary to account for this component in the modeling process. For the models described below, we approximate the WD spectrum as a 9750 K blackbody, normalized at 1.00 μm to a flux of $2.41 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Schwope et al. 2007; hereafter “S07”).

3. Cyclotron Modeling

As is evident from the infrared spectra presented in Fig. 1, the changing cyclotron emission is the primary cause of the near-infrared photometric variations of EF Eri. The spacing of the harmonics seen in these data are consistent with field strengths near $B = 13 \text{ MG}$. Given the coverage of at least five harmonics, we can attempt to derive the conditions that give rise to this emission, and attempt to localize the accretion region(s) on the white dwarf. For this purpose we will employ a simple cyclotron modeling code.

3.1. An Introduction to Constant Lambda Modeling

For magnetic field strengths displayed by the primary stars of polars, the cyclotron spectrum transitions from optically thick to thin at optical and/or near-IR wavelengths, making complex radiative transfer calculations necessary to model the emitted spectrum. As we shall see, “constant lambda” (CL) models provide a straightforward prescription by which the emerging cyclotron spectrum can be calculated using four parameters, all tied to global properties at the accretion spot.

In the accretion column, the plasma is dispersive and birefringent. Ramatay (1969) showed that in the large Faraday rotation limit of such a plasma, $\phi \gg 1$, where $\phi = \frac{e^3 \lambda^2}{2\pi m^2 c^4} \int_0^s n_e \vec{B}(s) ds$, it is possible to decouple the radiative transfer into two magnetoionic modes (ordinary and extraordinary). In this case, the radiative transfer equation reduces to $I_{o,e} = I_{RJ}[1 - \exp(-\tau_{o,e})]$ where the *o* and *e* indicate the ordinary and extraordinary modes, respectively. The total intensity is taken to be the sum of the ordinary and extraordinary modes.

The optical depth, τ , can be parametrized in terms of a dimensionless optical depth (or “size”) parameter Λ : $\tau_{o,e} = \Lambda\phi_{o,e}$ where $\Lambda = l\omega_p^2/(c\omega_c)$. l is the path length through the plasma, ω_p is the plasma frequency, $\omega_p = (4\pi Ne^2/m)^{1/2}$, and ω_c is the frequency of the cyclotron fundamental, $\omega_c = eB/mc$, with m being the relativistic mass of the gyrating particles. In the above formulation, the dimensionless absorption coefficient $\phi_{o,e}$ is dependent on B , the magnetic field strength, Θ , the viewing angle with respect to the magnetic field, and T , the isothermal temperature of the emitting slab. By integrating the emissivity of the gyrating electrons over an assumed relativistic Maxwellian distribution, Chanmugam & Dulk (1981; CD81) produced a general formulation of the cyclotron absorption coefficients.

These CL models, so called because the emergent radiation is assumed to be due to a single path through a slab of uniform optical depth parameter, Λ , were used with great success in the past (see Wickramasinghe and Meggitt, 1985a; Schwöpe, 1990). CL cyclotron models depend on four distinct global variables mentioned previously: B , T , Θ , and $\log(\Lambda)$. Because altering those four parameters causes complex, quasi-degenerate changes in the spectra produced, we briefly examine the influence of each parameter on the emerging cyclotron spectra below. These effects are detailed in Fig. 2.

The magnetic field strength is the most independent of the four parameters used, as increasing B merely shifts the position of each harmonic blueward. Increasing the plasma temperature has two main effects. Primarily, it causes the harmonics to grow. But as they bleed upwards they eventually “saturate” at the Rayleigh-Jeans limit (proportional to λ^{-4}), effectively becoming a black-body source. Because the lower harmonics saturate first, higher harmonics contribute ever more of the total flux with increasing temperature. Also, because the humps are the product of an ensemble of electrons emitting over a temperature distribution, higher temperatures increasingly populate the wings of the relativistic Maxwellian, broadening each harmonic as a result. Unfortunately, each of these affects can also be reproduced by increasing $\log(\Lambda)$, the “size parameter” of the system. Because the temperature does produce a small systematic shift in the position of the harmonics, it is possible in theory to decouple the affects of temperature and the size parameter. However, in practice, identifying this shift is difficult. Finally, varying the viewing angle changes the spectrum in two ways. First, viewing angles near 90° produce “peaky” harmonics with the higher orders pumped up. Also, as the viewing angle decreases from 90° , the harmonics shift blueward. This viewing angle induced shift then creates a periodic motion in the position of the harmonics over the orbit as the viewing angle ranges between its minimum and maximum values.

3.2. One-Component Cyclotron Models

The *JHK* light curves of EF Eri presented in H04 were phased using the Bailey et al. (1982) photometric ephemeris, which was also used to phase the current work. The *H*- and *K*-band lightcurves had minima at $\phi = 0.9$ and amplitudes of 0.7 and 0.8 mag, respectively. Remarkably, the *J*-band lightcurve was nearly anti-phased to *H* and *K* bands, with a minimum occurring at $\phi = 0.4$. These broadband variations can be deduced from the changing morphology of the *JHK* spectra seen in Fig. 1. We will show that cyclotron emission is the dominant source for EF Eri’s infrared variations.

Qualitatively, the *H* and *K* variations are due to a gradual increase in the size of the cyclotron harmonics in those bands from $\phi = 0.00$ to 0.50, and their subsequent decline thereafter. While the gradual growth in the cyclotron features is readily apparent in the *H*-band, in the *K*-band, the arbitrary flux offset and relative flatness of the mostly optically-thick ($n = 4$) cyclotron harmonic conspire to make its growth less obvious in Fig. 1. Nevertheless, the *K*-band flux (averaged over the range 2.02 to 2.44 μm) increases from $\lambda F_\lambda = 5.42 \times 10^{-13}$ to 1.06×10^{-12} $\text{erg s}^{-1} \text{cm}^{-2}$ over the interval $\phi = 0.01$ to 0.45. The source of the variation in the *J*-Band is also apparent in the SPEX data. From $\phi = 0.79$ to 0.29 the spectrum in the *J*-band is flat, with a slight photometric upturn at its shortest wavelengths. Over the interval $\phi = 0.34$ to 0.63, however, the *J*-band slope is qualitatively steeper, causing the brief *J*-band minimum seen in the light curve.

We produced cyclotron models using a CL code first developed by Schwöpe et al. (1990), co-adding the cyclotron spectrum with that of a 9750 K blackbody, normalized to the S07 WD flux. Because of the telluric features, and the low signal-to-noise of our spectra, an automated least-squares minimization procedure was not employed. Rather, we used published constraints for each parameter from the literature as well as our own modeling experience to hone in on the “reasonable” section of possible parameter space. First-order formulations for the wavelength dependence of the observed cyclotron humps with field strength (c.f. Wickramasinghe & Ferrario, 2000) imply fields of order 14 MG for EF Eri. This value is similar to the primary field strengths cited previously. We produced models covering the range of $10 \leq B \leq 21$ MG. Constraining the plasma temperature was more difficult, and required us to investigate a large range for this variable. In the end, we generated models from a lower limit of $kT = 1$ keV, up to the published high-state temperature of $kT = 14.0$ keV (Done et al., 1995). For both low angles, and low values of $\log(\Lambda)$, cyclotron harmonics become indistinct with hardly any flux in the higher ($n \geq 4$) harmonics. Based on this knowledge, and the fact that multiple distinct cyclotron features are obvious in our data, we only fit models with $\Theta > 35^\circ$ and $1.5 \leq \log(\Lambda) \leq 7.5$.

Our model spectra are shown in Fig. 1, with their phase-dependent parameters listed

in Table 1. The magnetic field strength varied slightly, with a mean value of 12.65 MG and a range of ± 0.15 MG. The plasma temperature was found to have a nearly constant value of $kT = 4.5$ keV, increasing to 5.5 keV near $\phi = 0.63$. Meanwhile, Λ changed by a factor of 2, varying between $5.4 \leq \log(\Lambda) \leq 5.7$, with the minimum occurring near phase 0.60, and the maximum near $\phi = 0.30$. Finally, the viewing angle has a maximum of 66° at $\phi = 0.95$, and a minimum at $\phi = 0.34$, where $\Theta = 51^\circ$. We list reduced chi-squared values, χ_ν^2 , for our fits in Table 1.

Because of the relative simplicity of this one component model, extracting the system geometry is straightforward. We take the system inclination to be $i = 58^\circ$, the mean value of the viewing angle in our models. The modulation to the viewing angle over an orbit is due to the magnetic colatitude of the accretion spot rotating into and away from our line-of-sight. We find that a magnetic colatitude of 6° produced a series of viewing angles consistent with our data.

3.3. Two Component Cyclotron Models

The single component CL models provided excellent fits to the spectra for two thirds of the orbit. But, as shown by the values of χ_ν^2 in Table 1, failed to provide the same quality fits near $\phi = 0.5$. This is due to the deviation of the spectra from our models first seen near $\phi = 0.34$, predominately affecting the regions shortward of $1.6 \mu\text{m}$. To better match the evolving spectra, we constructed two-component models, created by coadding two cyclotron models together, each with independent values of B , T , Θ , and Λ . In summing these two models we continually adjust the relative contribution of the two cyclotron components, normalized to the observed spectrum in the K -band. Table 2 lists the best-fit values for B , T , Θ , and Λ , as well as the flux-weighting factor (“F”) at each orbital phase. We also include the resulting χ_ν^2 values for these fits.

Figure 3 depicts the contribution from each of the cyclotron components, an optically thinner component (hereafter “thin”) and an optically thicker (“thick”) component. As shown in table 2, the thin component is cooler, with an average temperature of approximately 1 keV lower than the thick component. The final spectra (shown in green) are the composites of both cyclotron models added to the normalized WD discussed previously. The two component models do a better job of explaining the changing morphology of the spectra with substantially improved χ_ν^2 values in the phase interval $0.34 \leq \phi \leq 0.63$.

In Fig.4 we show how the properties of each of the two cyclotron components change over an orbit, including synthetic lightcurves derived from our two component fits. The

changes in the J -band spectra are explained by the fact that near phase 0.00 the thin and thick components are approximately equal. Between $\phi = 0.11$ and 0.56, the flux from the thin component slowly declines, while that from the thick component increases by a factor of six. Our models do not perfectly reproduce the J -band light curve. As shown in Fig. 4, the light curve of EF Eri in the J -band is complex, with large photometric variations on timescales as short as $\Delta\phi \leq 0.10$. To obtain a reasonable S/N, we have had to median a number of spectra together, and this process limits our ability to detect variations on time scales of $\Delta\phi \lesssim 0.15$. The main discrepancy between the light curve derived from the models, and that derived from photometry occurs at $\phi = 0.46$. The origin for this difference cannot be identified given the low temporal resolution of our medianed spectra.

Our two component models provide a much better explanation to the origin of the changes seen in the light curves of the H -, and K -bands. In the H -band, the thin component dominates near $\phi = 0.00$. Over the orbit, this component stays roughly constant, while the flux from the thick component peaks sharply near $\phi = 0.40$. Simultaneously, the contribution from the thin component reaches a minimum as the thick component peaks. These changes, working in concert, explain the flat H -band maxima. The morphology in the K -band is similar to the H -band, but with a smaller contribution from the thick component. Both the thick and thin components produce fluxes that increase through the first half of the orbit, and then decline afterward. The more rapid decline of the thick component at $\phi = 0.63$ reproduces the light curve feature seen at that phase.

Table 2 summarizes the model parameters for the two component model fits over an entire orbital cycle. The thick component has a nearly constant magnetic field strength (12.6 MG) and temperature ($\simeq 6.0$ keV). The viewing angle of this component changes from 60° to 56° over the orbit. $\log(\Lambda)$, meanwhile, slowly increases for the first half of the orbit after which it declines. The thin component, by contrast, has a slightly cooler temperature $\simeq 5.0$ keV, with a magnetic field strength which varies between 12.5 and 12.9 MG. The viewing angle of this component varies between 64° and 53° . Finally, $\log(\Lambda)$ of this component declines slowly from 5.5 at $\phi = 0.01$ to 4.9 at $\phi = 0.45$. Afterward, the trend is reversed, reaching $\log(\Lambda) = 5.6$ at $\phi = 0.99$.

3.4. GALEX Observations of EF Eri

Szkody et al. (2006) presented GALEX observations of EF Eri. The results were somewhat surprising, showing significant ultraviolet emission that was highly variable. In fact, the amplitude of the variability in the FUV bandpass was nearly identical to that seen in the H - and K -band light curves. Szkody et al. attempted to model the combined FUV,

NUV and V -band light curves as the sum of a WD + hotspot. While such models could explain both the SED and UV light curves, they were unable to simultaneously explain the V -band light curve without invoking unusual limb darkening laws. More recently, S07 has shown that inclusion of a proper WD atmosphere models produced much better fits to the multi-wavelength light curves.

Given the similar amplitudes of the UV and IR variability, and nearly identical values of $L_{bol}(\text{IR})$ and $L_{bol}(\text{GALEX})$, could cyclotron emission be partly/mostly responsible for the variations seen in the UV light curves? Obviously, producing significant cyclotron flux in the UV requires much higher field strengths than used for modeling our near-IR data. But model tomographic maps of Beuermann et al. (2007), indicate that regions of very high field-strength appear to be present in EF Eri.

To explore the possibility of UV cyclotron emission in EF Eri, we have used the same parameters for the cyclotron emission as found in the one-component models for our SPEX data, except that we adjusted the magnetic field strength to allow for UV cyclotron emission. While the value of model parameters is most likely different in the UV than in the near-IR, we have few constraints on the possible emission from this high field component, and intend this merely a starting place for modeling work. Furthermore, because of the discrepancy between the spectrum of a blackbody and an actual white dwarf atmosphere in the UV/optical, we have replaced the our 9750 K blackbody with a synthetic white dwarf spectrum ($T = 9500$ K, $\log g = 8$, solar metalicity, I. Hubeny, private communication). Our results are shown in Fig. 5 for the phases of maximum and minimum UV fluxes ($\phi = 0.45$ and 0.95 , respectively). These models have identical values of T and Θ as the models shown in Fig. 1, but with $B = 115$ MG. This field strength is similar to the $\simeq 100$ MG spot inferred in Beuermann et al. 2007. Such models do an excellent job of matching the minimum light spectral energy distribution (SED) from the FUV to the I -band. However, to account for the FUV photometric flux observed during the bright phases, we had to increase $\log(\Lambda)$ from 5.7 to 6.2 (the value of Λ for the faint state was identical to our near-IR models). Further insight into the source of the UV variability of EF Eri will be gained once phase-resolved spectroscopy at these wavelengths becomes available.

4. Discussion

The fact that our one component models fail in the J -band, despite their success in the H - and K -bands, motivated us to generate two component fits for EF Eri. These two component models resulted in substantially better fits at every orbital phase, though they also do not fully explain the morphology seen in the J -band near $\phi = 0.5$. The magnetic

field strengths we derive are consistent with those previously reported. It is interesting to note that Ferrario et al. (1996) also required a two component model to explain their phase-averaged, high-state infrared spectrum of EF Eri. In that case, however, moderately higher magnetic field strengths were necessary.

The high plasma temperatures that we require for our models is surprising given the long-lived low state of EF Eri, and the expectation that the associated mass accretion rate is very low, possibly in the “bombardment scenario” regime (Kuijpers & Pringle 1982). But the presence of the $n = 7$ harmonic indicates the plasma temperature cannot be extremely low. Comparison of plasma temperatures derived from X-ray observations for other polars in low states are in agreement with what we find for EF Eri. For example, Ramsay et al. (2004) presented data on 16 polars in low-states (\dot{m} below $10^{-2} \text{ g s}^{-1} \text{ cm}^{-2}$), of which 7 were detected at sufficient levels to allow their plasma temperatures to be modeled. They derived temperatures that ranged between 1.4 and 5.0 keV, demonstrating that despite the low values of \dot{m} in these systems, some polars can maintain moderately high plasma temperatures.

Until this year, only the high-state temperature for EF Eri had been modeled using X-ray data. Done et al. (1995) used GINGA to fit a Raymond-Smith spectrum with $kT = 14 \text{ keV}$, with a maximum temperature of 25 keV, a value close to temperatures predicted by strong-shock models. S07 have recently used XMM-Newton to detect EF Eri in its low state. The spectrum was fit as a MEKAL plasma with a temperature of $2.8 \pm 1.7 \text{ keV}$. This temperature compares reasonably well to those obtained by in Ramsay et al. (2004) for other low \dot{m} polars in the X-ray, but is lower than the temperatures derived here; possibly because the X-ray emission and the cyclotron emission modeled here are generated at different regions of the shock. More pertinently, Fischer & Beuermann (2001) have produced normalized temperature and density profiles in the accretion column of polars, running through many lines of sight of the cooling plasma to add a layer of realism beyond standard CL modeling. For EF Eri, assuming $B = 13 \text{ MG}$ and $\dot{m} = 1 \times 10^{-2} \text{ g s}^{-1} \text{ cm}^{-2}$ they found a maximum temperature of 7 keV, consistent with our results. CL models may inherently require slightly higher plasma temperatures than are actually present. Rousseau et al. (1996) compared cyclotron models that included an ensemble of mass accretion rates (each with an associated plasma temperature), to the results from a single CL model for UZ For. They found that the CL model required temperatures at high end of the range when compared to those seen in the multiple accretion rate model, indicating that perhaps CL plasma temperatures are systematically hot.

4.1. The Accretion Region Geometry

As discussed earlier, it is simple to explain the single-component cyclotron model evolved in section 3.2: the cyclotron emission comes from a region with a magnetic colatitude of 6° (with $i = 58^\circ$). But a single cyclotron component did not fully explain the evolving morphology of the spectra. Thus we added a second cyclotron emission component. The two component model resulted in substantially better fits throughout the orbit. We can derive insight into the geometry of the cyclotron emission from this two component model by analyzing the modulation of the viewing angle of each component over an orbital cycle. The viewing angle, Θ , is defined as:

$$\Theta = \cos^{-1}(\cos(i)\cos(b) - \sin(i)\sin(b)\cos(2\pi\phi)), \quad (1)$$

here i , is the orbital inclination angle, b is the angle between the rotation axis and the direction of the *local* field line at the accretion region, and ϕ is the orbital phase. It is important to note that b can be different from the magnetic colatitude, β , which is defined as the angle between the rotation axis and magnetic axis. For example, in ideal, dipolar accretion (which is almost certainly not the case in EF Eri), the diverging field lines produce an approximate relationship of, $b \simeq \beta + 3/2\alpha$ (see Beuermann et al. 1987), where α is the angular distance from the magnetic axis. Due to the large angular extent of the accretion regions observed for most polars, b can exhibit significant variations from the core to the edge of the accretion spot.

In our two component model, the viewing angles of the thin and thick components range from 64° to 53° and 60° to 56° , respectively. For the inclination we used $i = 58^\circ$, the mean value of the viewing angle in both the thin and thick components. This value agrees with the inclination angle derived by Piirola et al. 1987 ($i = 55^\circ \pm 3$). We can then fully specify the viewing angle at a given orbital phase once b , the field line angle, is determined. In a simple accretion picture, with a constant magnetic field, the magnetic co-latitude β will be equivalent to the field line angle b . While departures of up to 0.4 MG are evidenced in our models, this amplitude represents only three percent of the magnetic field strength locally active. As such, we consider the magnetic field strength to be nominally fixed, and constant. The magnetic co-latitude, β , is then just the maximum deviation of viewing angle, from the orbital inclination of the system. Thus, the magnetic co-latitudes of the thin and thick components are 6° and 2° respectively.

Our accretion geometry is generally consistent with the picture derived from high-state X-ray observations. Beuermann et al. (1987) found that the accretion region of EF Eri resembled an “X-Ray auroral oval”, showing an extended, diffuse tail of $\simeq 20^\circ$, with a

compact nucleated core near the rotation axis. The difference of course, is that the X-ray emission comes directly from the shock, while the cyclotron emission is preferentially emitted at right angles to this feature. In addition, the actual structure of this feature could have changed dramatically as EF Eri dropped into its low state. In practice, our two cyclotron component model has taken this extended and structured shock and reduced it to two discrete spots: the thick component, which corresponds to the core of the accretion arc and the thin component which corresponds to the tail. However, the two cyclotron emission regions are only separated by four degrees, and it a distinct possibility that the two components could correspond to local variations of a single accretion spot.

As previously mention, our motivation for running two component models largely resulted from our inability to explain the excess emission of the J -band near $\phi = 0.40$. To some extent, these more complex models were a success. However, we still fail to adequately reproduce the far blue-end of the spectra, a fact which may necessitate the need for additional emission components. If cyclotron emission from accretion on to very high field strengths is actually present in EF Eri, then those components could introduce an additional contribution to the J -band (note that the $n = 1$ harmonic for $B = 100$ MG is at $1.07 \mu\text{m}$).

4.2. Where is the Secondary Star in EF Eri?

Above, we discussed a model for the cyclotron emission from EF Eri that appears to be reasonable, and explains the large amplitude variations seen in its near-infrared light curves. As a consequence, the cyclotron models leave little room for emission from the expected low mass secondary star (but note the small “excess” at the red end of the K -band seen in many of our spectra). With these cyclotron models, we can attempt to put additional limits on the nature of this object.

Beuermann et al.(2000) and H04 have shown that secondary star in EF Eri must have a spectral type later than M9 to be consistent with its observed spectral energy distribution. Howell et al. (2006b) have used radial velocity observations to show that the secondary appears to have a sub-stellar mass. While the model fits to the observed spectra are not perfect, it is difficult to have a *significant* source of additional infrared luminosity in this system. For example, if the secondary star is an L-dwarf, it must supply less than 25% of the K -band flux (at K -band minimum) to be consistent with the observed spectrum.

The observed magnitude at light curve minimum is $K = 15.65$ (H04). Thorstensen (2003) has published a parallax for EF Eri, with the formal result of $d = 163 (+63/-50)$ pc. Including priors that include the Beuermann et al. (2000) result for the white dwarf, and the

sizable proper motion, they arrive at a lower distance of 113 (+19, -16) pc. Using the entire possible range in distance (97 to 226 pc), and assuming the secondary star supplies $\leq 25\%$ of the K -band luminosity, the maximum observed absolute magnitude for the secondary of EF Eri is in the range $11.9 \leq M_K \leq 10.1$, completely consistent with the presence of a brown dwarf secondary.

5. Conclusion

We have presented new, phase-resolved low resolution spectra of EF Eri that demonstrate its near-IR SED is dominated by cyclotron emission. We have constructed models using a CL prescription that is reasonable, and can explain the large amplitude variations observed in its JHK light curves. In addition, we also show that cyclotron emission may be responsible for the GALEX observations of EF Eri. Given the complex magnetic field structure of EF Eri, near-IR observations of higher temporal cadence would be extremely useful in unraveling the accretion geometry in this system, but will require an 8-m class telescope.

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Table 1. Parameters for the One Cyclotron Component Models

Phase	B (MG)	T (keV)	Θ	$Log(\Lambda)$	χ^2_ν
0.01	12.6	4.5	64.0	5.7	1.36
0.11	12.6	4.5	62.0	5.9	1.39
0.23	12.6	4.5	58.0	5.6	2.06
0.29	12.5	4.5	56.0	6.0	1.35
0.34	12.6	4.5	51.0	5.7	2.05
0.45	12.6	4.5	55.0	5.7	2.58
0.56	12.6	4.5	58.0	5.7	2.29
0.63	12.8	5.5	58.0	5.4	2.35
0.79	12.8	5.0	60.0	5.5	1.36
0.95	12.8	5.5	66.0	5.6	1.26
0.99	12.6	5.0	66.0	5.6	1.33

Table 2. Parameters for the Two Cyclotron Component Models

Phase	F_1	F_2	B_1 (MG)	B_2 (MG)	T_1 (keV)	T_2 (keV)	Θ_1	Θ_2	$\text{Log}\Lambda_1$	$\text{Log}\Lambda_2$	χ^2_ν
0.01	0.88	0.12	12.6	12.5	4.5	6.0	64.0	60.0	5.5	6.4	1.20
0.11	0.88	0.12	12.6	12.6	5.0	6.0	61.0	60.0	5.5	6.5	1.31
0.23	0.82	0.18	12.8	12.5	5.0	6.5	59.0	59.0	5.0	6.5	1.32
0.29	0.85	0.15	12.6	12.5	5.0	6.0	57.0	58.0	5.3	6.5	1.32
0.34	0.82	0.18	12.7	12.5	5.0	6.5	55.0	57.0	4.9	6.6	1.21
0.45	0.78	0.22	12.7	12.5	5.0	6.5	53.0	56.0	4.9	6.6	1.83
0.56	0.70	0.30	12.5	12.5	5.0	6.0	55.0	56.0	4.9	6.6	1.82
0.63	0.81	0.19	12.9	12.6	5.5	6.5	57.0	58.0	4.9	6.6	1.72
0.79	0.85	0.15	12.7	12.6	5.0	6.0	60.0	59.0	5.2	6.4	1.10
0.95	0.90	0.10	12.7	12.6	5.0	6.0	63.0	60.0	5.6	6.4	1.41
0.99	0.88	0.12	12.6	12.6	5.0	6.0	64.0	60.0	5.6	6.4	1.51

Note. — Subscripts '1' and '2' refer to the thin and thick components respectively. F_1 and F_2 show the relative contribution of each cyclotron component to the flux at 2.19 microns.

Figure 1. One-component model fits to the IRTF/SPEX dataset for EF Eri. At each phase, the SPEX data are shown in black. The best fit cyclotron component is added to a 9750 K blackbody which is normalized to match the $1\ \mu\text{m}$ WD flux in S07, to yield the composite model (green). At each phase, both the SPEX data and models are offset by a constant increment of $1.0 \times 10^{-12}\ \text{erg s}^{-1}\ \text{cm}^{-2}$ from the previous spectrum: the bottom spectrum corresponds to the labeled flux. The orbital phases are printed on the far right margin for 17 August 2004 (black) and 14 January 2007 (blue). Above the bottommost spectrum the cyclotron harmonic numbers are indicated.

Figure 2. Variations on a Theme: Cyclotron Modeling. In the four following boxes a nominal cyclotron model with $B = 30\ \text{MG}$, $kT = 5\ \text{keV}$, $\Theta = 80^\circ$, and $\log(\Lambda) = 3$ is varied. Increasing values for each parameter proceed upward in each box. In panel (a) the magnetic field, B , changes from 10 to 35 MG with 5 MG steps. (b) we alter the temperature from 1 to 25 keV in steps of 5 keV. (c) $\log(\Lambda)$ is varied from 1 to 6 in steps of 1. (d) Θ changes from 30° to 80° , with steps of 10° . In each of the model sets we normalize the harmonics relative to each other. The absolute fluxes are arbitrary.

Figure 3. Two-component fits to the IRTF/SPEX spectra (black), showing the thin (red) and thick (blue) cyclotron components. (a) Phases 0.00 to 0.34. (b) Phases 0.45 to 0.99. The green line is the composite of both cyclotron models and the normalized 9750 K blackbody (cyan shown plotted for $\phi = 0.01$). All spectra are sequentially offset by $\lambda F_\lambda = 1.5 \times 10^{-12}\ \text{erg s}^{-1}\ \text{cm}^{-2}$.

Figure 4. (a) Orbital variations of relative parameters in the 2-component models. The top panel shows the H04 J -Band lightcurve. The second panel shows a synthetic lightcurve constructed by integrating the model spectra through the J bandpass for both the thin (red) and thick (blue) components as well as their composite (green). Panels 3-5 document how kT , θ , and $\log(\lambda)$ change from both the thin and thick components over the orbit. The solid triangles are plotted for phases which correspond to those listed in Table 2.

(b) The H and K band lightcurves as shown in Fig. 4a.

Figure 5. GALEX and optical photometry from Szkody et al. 2006. The points in red are at the UV/Optical minimum ($\phi = 0.38$). Likewise, in blue are the data from the maximum ($\phi = 0.85$). The cyclotron + WD models (also in blue and red) shown are nearly identical to the corresponding IR model at similar phase to the GALEX observations, but now with $B = 115\ \text{MG}$.













